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A Novel Simple Miniaturization Technique for Microstrip Couplers

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Abstract. This paper analyzes the new compact design of couplers based on the use of microstrip lowpass filters. The proposed design achieves significant reduction in coupler size while obtaining the same characteristics as of the conventional coupler. Prototype of the coupler with the central frequency of 1 GHz was produced on the substrate with dielectric permittivity of 4.4. The experimental results showed good agreement with numerical simulations. The size of the rat-race coupler was reduced by 83.7%.

1. Introduction

There are various papers covering different RF devices miniaturization methods. This trend in modern RF design is primarily due to the increasing complexity of microwave circuits and increasing number of handheld devices, which require all-in-one small integral circuit solutions. Except reducing the size of devices, it is important to maintain their characteristics. In this paper novel miniaturization technique of rat-race coupler is presented. Due to their useful properties the rat-race couplers are widely used in various areas of RF design. Let us consider the rectangular design with spacing between ports 1-2, 2-3, 1-4 a quarter wavelength and between 3-4 – three quarter wavelengths. The overall length of all the lines is equal to 1.5 wavelengths. This arrangement can provide both in phase excitation and antiphase excitation of output ports depending on the selection of the input port. Various methods of miniaturization could be applied to the couplers: slow-wave structures with meandered lines and open-circuited stubs [1], artificial transmission lines composed of microstrip quasi-lumped elements and their discontinuities [2], lines with asymmetrical T-structures [3], periodically loaded transmission lines [4], space-filling curves [5] and stepped-impedance ring resonators [6], shunt-stub artificial transmission lines [7], novel dual transmission lines [8]. In [9] surrogate modeling using auxiliary circuit models and space mapping is investigated. Comparison between different miniaturization methods is shown in Table 1.

Table 1. Comparison of different miniaturization methods

Miniaturization method	Comparative size	Central frequency, GHz
Conventional microstrip line	100%	-
[8]	21.87 %	2.5



[6]	21.5 %	2.5
Proposed method	16.3%	1
[5]	12.6 %	2.4
[9]	5.7 %	1
[1]	4.87%	0.9
[7]	3.9 %	0.9
[4]	32 %	1.8
[2]	9 %	0.9
[3]	5 %	0.9

However, these methods of reducing the size do not allow maintaining the characteristics of the device at the level of the conventional one. Moreover, they are far from intuitive use, mostly complicated in the design procedure and fabrication. The proposed method makes it possible to obtain significant size reduction while maintaining the characteristics. This method is based on replacing each line with a sequence of high- and low-impedance lines, acting as a lowpass filter with the same phase response as the replaced line. Proposed technique was implemented for miniaturization of the quadrature-3dB couplers and the results are presented in [10].

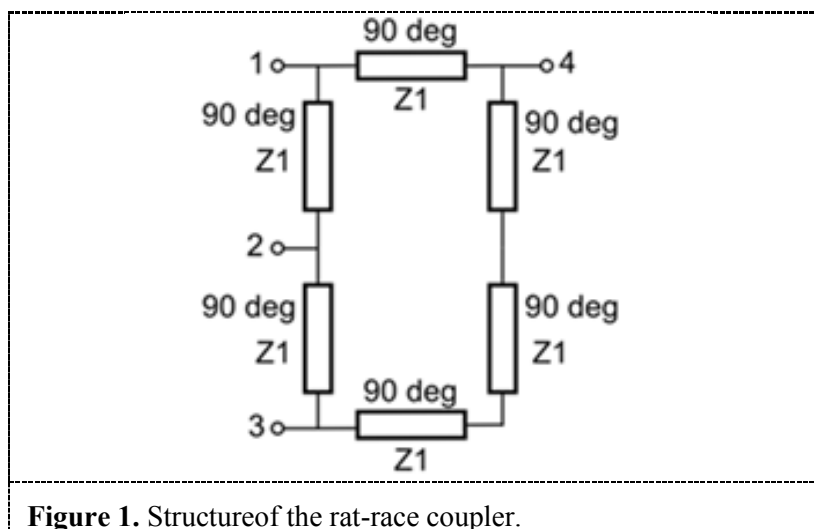


Figure 1. Structure of the rat-race coupler.

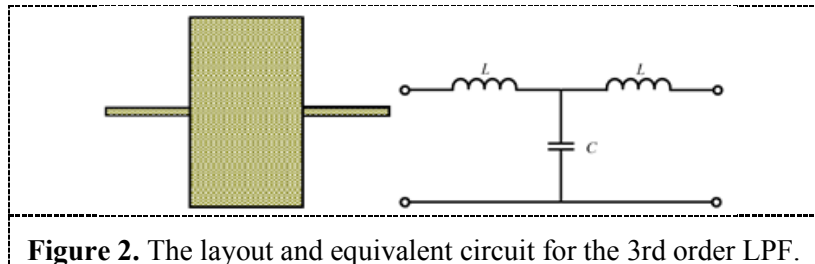
2. Conclusion Design procedure

First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. In this paper microstrip rat-race coupler design is investigated. Its structure is shown in Fig. 1. The central frequency of the designed coupler is 1 GHz and the substrate used is 1 mm height with dielectric permittivity of 4.4 and $\tan \delta = 0.02$.

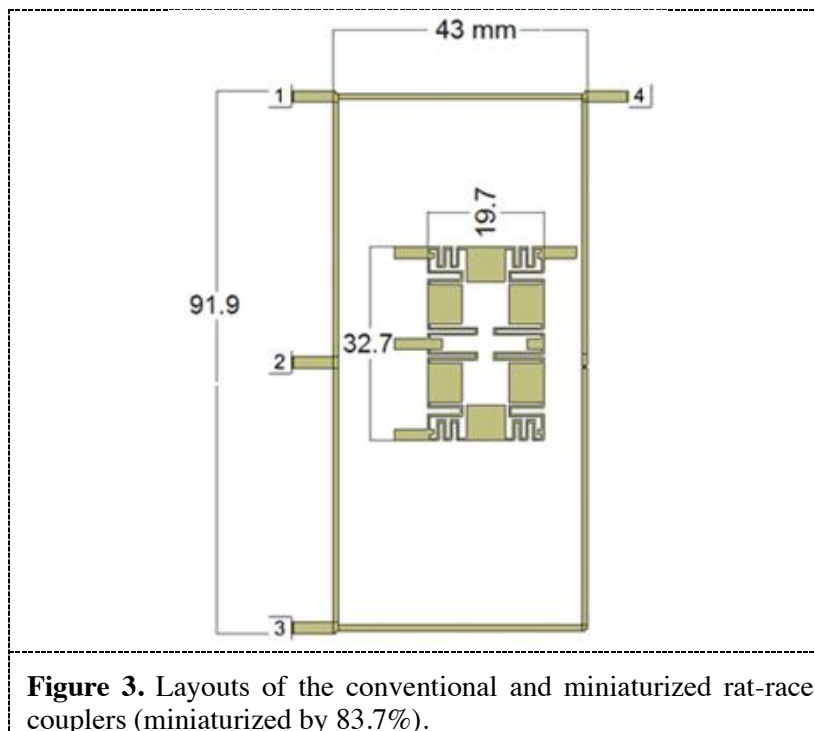
The aim of this research was to reduce the size of the coupler while maintaining its characteristics. For further comparison, conventional design of coupler was produced. The rat-race coupler with the central frequency of 1 GHz, has an area of 3951 mm² and the operating frequency band based on the isolation level of -20 dB, is 328 MHz (from 831 to 1152 MHz). Dimensions of the layout are determined by the physical size of the quarter wavelength sections. It can be concluded that the rat-race coupler does not use the free space in the inner area of the layout. The free space inside the device occupies more than 92% of the whole area. The first step in miniaturization is to synthesize microstrip

lowpass filter with the wave impedance of 70 Ohms and a phase response of 90° at the operating frequency of the device.

The layout and equivalent circuit for the LPF are presented in Fig. 2. It should also be noted that to achieve the desired phase response and compact size it is required to correctly select the order of the filter to find compromise between its size and insertion loss in the working band. Usually the cutoff frequency of the LPF is much higher than the central frequency of the working band, and the higher the order of the designed filter the higher its cutoff frequency.



After the filters are designed, they are combined into one circuit. Further size reduction is achieved by changing the shape of high impedance lines (while keeping their electrical and physical lengths the same), and moving low impedance segments to the inner area. Due to this further reduction of physical size of the device can be achieved. As a result, the layout of the miniaturized rat-race coupler is obtained, and shown in comparison to conventional design in Fig. 3.



This design consists of lowpass filters configured to obtain specified input and output impedance and providing desired phase response at the central frequency, it has dimensions of $32.7 \times 19.7 \times 1$ mm that is 83.7% less than the conventional design. Further reduction of the size of the coupler is complicated by the appearance of parasitic capacitance in close proximity of adjacent conductive elements of lowpass filters. Fig. 4 shows the dependencies of the S-parameters versus frequency of the coupler. The operating band in terms of the isolation level of -20 dB is 271.4 MHz. Return loss of input

port is -17 dB at the central frequency. The maximum level of return loss at the central frequency was not achieved because the electrical lengths of microstrip lines between the ports are not exactly equal to 90° and 270° . The imbalance of power split ratios is 0.125 dB. The phase difference between the in-phase output ports is about 2° at the central frequency (Fig. 5).

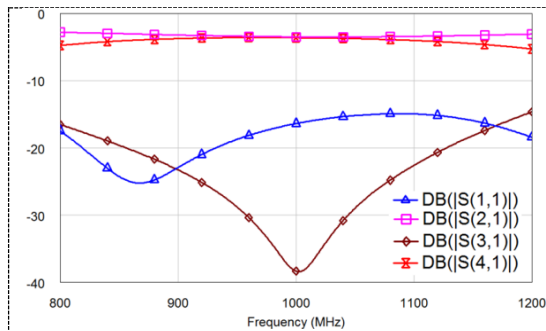


Figure 4. The simulation results of the miniaturized rat-race coupler.

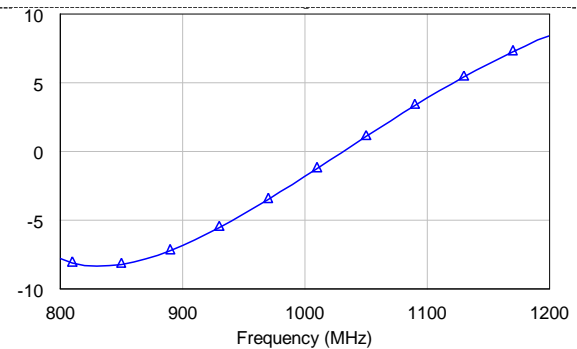


Figure 5. Graph of S-Parameters versus Frequency The phase difference between the in-phase output ports.

Prototype

This design is feasible and workable as it provides equal power splitting between output ports in a wide frequency range. To obtain experimental results the prototype of the proposed design was produced (Fig. 6) and measured using a vector network analyzer R&S ZVA24 operating in the frequency range from 100 MHz to 24 GHz and for accurate results calibration kit ZV-Z52 was used.

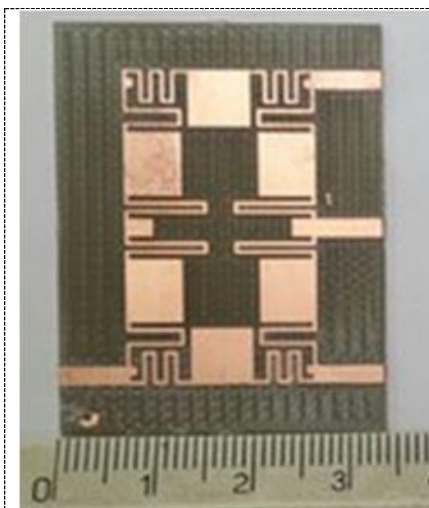


Figure 6. Miniaturized coupler

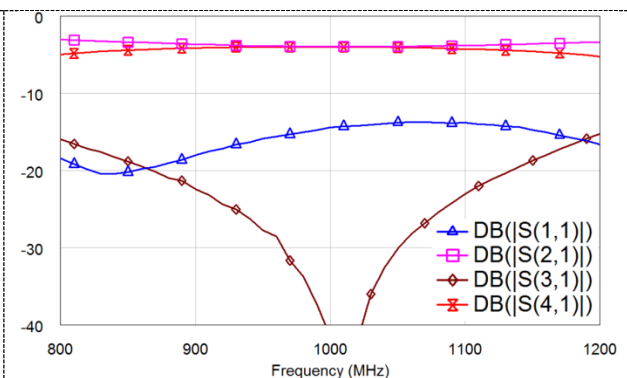


Figure 7. The measured characteristics of the miniaturized rat-race coupler.

Table 2. Summarized measured characteristics of the couplers

	Bandwidth (–20 dB isolation), MHz	Area, mm²
Conventional rat-race coupler	327	3951
Miniaturized rat-race coupler	271	644.2

3. Conclusion

In this paper the method of miniaturization of rat-race coupler has been described and investigated. Miniaturization of the coupler is based on replacing the microstrip lines with their equivalents in the form of LPFs with the same phase responses at the central frequency. To verify efficiency of the proposed technique, microstrip prototype with the central frequency of 1 GHz was simulated and manufactured. At sufficiently significant miniaturization of the rat-race coupler by 83.7% the characteristics of the device with minor changes were kept. The operating frequency band by the level of isolation of –20 dB was reduced by only about 15%. It shows the efficiency of the method for broadband devices –the ability to reduce the size in a wide band while maintaining the same characteristics. This method of miniaturization has shown its efficiency and has the advantages such as high speed of design, simplicity and efficiency of miniaturization.

4. Acknowledgements

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